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VELOPING FLIGHT TEST TECHNIQUES TO ENSURE PROPER RIGGING OF HIGHLY AUGMENTED AIRCRAFT

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Abstract

Uncommanded rolling moments have been considered a natural part of the aging process of some F/A-18 airplanes. These rolling moments can range from an annoyance requiring constant trimming to a serious degradation in handling qualities which can cause premature departures during maneuvering flight. Uncommanded rolling moments in flight can generally be eliminated with rigging if the surface which is causing the roll is known. Due to the highly augmented flight control architecture of the F/A-18, it is very difficult to isolate the actual control surface that is causing the uncommanded rolling moment since so many surfaces are active. NAWC-AD has developed techniques to identify the flight control surface causing uncommanded rolling moments. These techniques have been used successfully on four F/A-18 airplanes to identify which flight control surface was causing uncommanded roll rates. Additional flight tests are planned to further refine the techniques described in this paper. These techniques have been demonstrated to reduce uncommanded rolling moments in the F/A-18 and can be applied to all aircraft.

Nomenclature

ACM	Air Combat Maneuvering
AOA	Angle of Attack
CR	Cruise (gear up, flaps auto)
FCC	Flight Control Computer
LEF	Leading Edge Flap
NAWC-AD	Naval Air Warfare Center Aircraft Division, Patuxent River, MD
PA	Power Approach (gear down, flaps full)
PA1/2	Power Approach (gear down, flaps half)
TEF	Trailing Edge Flap

Introduction

The maximum performance capabilities of any aircraft are highly dependent on the basic rig condition of the flight control surfaces. This is especially true for aircraft with highly complex digital flight controls, such as the F/A-18, which have multiple control surfaces active. To date, there are no formal in-flight procedures to test for proper aircraft rigging. As a result, uncommanded rolling moments have been considered a natural part of the aging process of some F/A-18 airplanes. These rolling moments can range from an

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annoyance requiring constant trimming to a serious degradation in handling qualities which can cause premature departure during maneuvering flight. The flight test techniques described in this paper have been used to identify and reduce the causes of uncommanded rolling moments and has resulted in improved handling qualities in the F/A-18 airplane.

Contractor Experience

New F/A-18 airplanes occasionally exhibit uncommanded rolling moments on the first flight; however, production acceptance standards prohibit delivery of an aircraft exhibiting "abnormal" roll-off characteristics. General agreement between the contractor and the customer resulted in the use of 3 deg/sec as the standard for unaccelerated flight (up to 20 deg AOA).

Acceptance test flights often identified the need for minor rigging adjustments of the flight control surfaces on new aircraft to reduce roll-off after take-off to less than 3 deg/sec. Only a few F/A-18's in the entire history of contractor acceptance testing required more than minor flight control rigging to correct excessive roll-off tendencies. The exceptions were airplanes with major mold line inaccuracies such as non-concentric radomes, mis-shaped canopies, or asymmetric TEF seal gaps.

Trial-and-Error Rigging

The flight acceptance testing process was a trial-and-error task, beginning with a general survey of the flight envelope for abnormalities. If excessive uncommanded roll rates were uncovered, identification of the possible sources of the roll-off was the main objective of the test pilot. Specifically, identification of the axis, AOA, airspeed, and quantity of the out-of-rig condition was necessary to establish an accurate history of performance. Each maintenance action was carefully recorded and the result correlated with the subsequent reduction in roll-off.

These trial-and-error procedures were successful at the contractor facility; however, they are not supported adequately with Technical Order procedures for use in the fleet. The major deficiencies of these procedures that preclude their inclusion in normal field maintenance work packages are: 1) the trial-and-error nature of the process, 2) the difficulty of identifying the source of the roll-off on such a complicated set of digital flight controls, 3) the training and experience required of both the test pilots and the maintenance crews, and 4) the lack of quantified rigging adjustments necessary to counter measured amounts of roll-off.

Fleet Experience

Many squadrons have individually restricted the flight envelopes of specific F/A-18 airplanes, and have occasionally grounded some airplanes, to prevent inadvertent departures. Several cases identified in the field led to contractor involvement and the successful application of these trial-and-error procedures on problem aircraft operated by the U.S. Navy and Marines and Air Forces in Spain, Australia, and Canada. Mutual interest in the solution of these rigging procedural problems led to collaboration between the contractor and NAWC-AD.

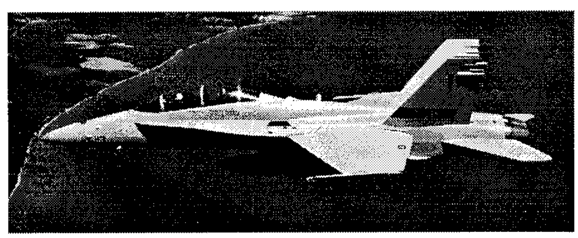
A False Paradigm

A common paradigm is that airplanes flown over a period of time are thought to undergo permanent deformation (fuselage bending) due to the stresses of flight, resulting in uncommanded rolling moments. Two airframes (an F/A-18A model and an F/A-18B model; reference 1) that exhibited uncommanded rolling moments were surveyed and a minor deformation was found to exist in the forward fuselages of both airplanes. It is suspected that the deformations occurred during the manufacturing process. In addition to the forward fuselage deformation, the F/A-18A was found to have a mis-shaped canopy and the flight control surfaces on the F/A-18B required rigging. Changing the canopy on the F/A-18A and re-rigging the flight control surfaces on F/A-18B eliminated the uncommanded rolling moments on both airplanes. The deformations in the forward fuselages were not corrected and do not have an adverse effect on the handling qualities of these airplanes. Therefore, fuselage bending is not necessarily a cause of uncommanded rolling moments to the extent previously documented. Furthermore, there is no evidence to suggest that airplanes undergo permanent fuselage bending as a result of flight stresses.

Rigging and Uncommanded Roll

Uncommanded rolling moments during unaccelerated flight can generally be attributed to flight control surface rigging, including such factors as location of the zero reference rig points, warped or bent flight control surfaces, and variation in rigging techniques between maintenance personnel. If all flight control surfaces are correctly rigged and are operating properly, the handling qualities of the airplane should be Level I (reference 2). However, in a small percentage of cases, though the flight control surfaces may be rigged properly, uncommanded rolling or yawing moments may still exist. Due to the highly augmented flight control architecture of the F/A-18, it is very difficult to isolate the actual control surface that is causing the uncommanded rolling moment since so many surfaces are active. There are no formal maintenance procedures to address pilot reports of uncommanded roll-off. Consequently, the aircraft is often grounded until all flight control surfaces are re-rigged. This process of flying/grounding/re-rigging is repeated until either the airplane's handling qualities are improved, the airplane is accepted as "bent", or the airplane is grounded. NAWC-AD is in the process of perfecting a very simple flight test method to identify the actual flight control surface that is causing the uncommanded roll-off. Once the surface is identified, specific maintenance actions to reduce or eliminate the uncommanded roll-off can be executed and the airplane returned to its full operational flight envelope.

The F/A-18 Airplane



Primary Flight Controls

The F/A-18 airplane incorporates a fully augmented fly-by-wire irreversible flight control system. The five primary flight control surfaces are the ailerons, twin rudders, differential/collective stabilators, differential/collective LEF's, and differential/collective TEF's. The FCC's command the primary flight control surfaces to produce Level I handling qualities from slow airspeed/high AOA flight conditions through the supersonic flight regime. Inputs to the flight control surface hydraulic actuators are provided by the two FCC's through the full authority control augmentation system. Stick and rudder feel are provided by spring cartridges.

The FCC's and the actuators accept the rigged position as the zero deflection position for each flight control surface. It is important to note that the only electrical feedback between the flight control surface and the FCC's is at the actuator. This means that although the FCC's may be commanding zero surface deflection, the surface may not be at exactly zero deflection. However, as long as the surface is rigged within the allowable tolerance, the airplane is designed to not exhibit any uncommanded rolling or yawing moments.

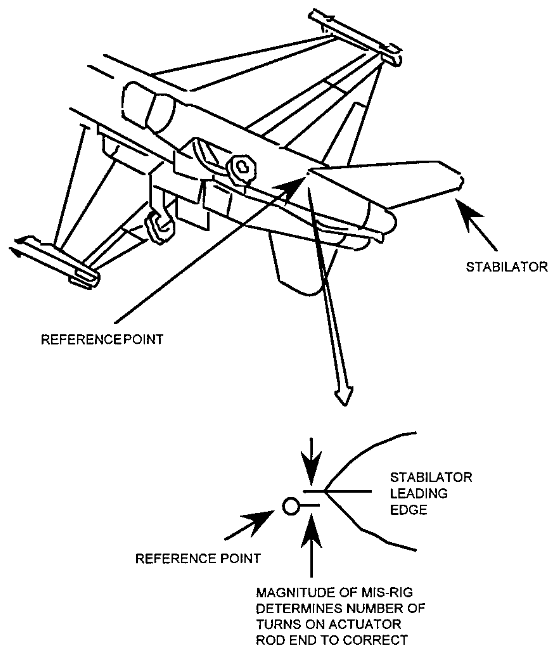


Figure 1
RIGGING REFERENCE POINT FOR THE F/A-18 STABILATOR

Flight Control Surface Rigging Procedures

The flight control surfaces are physically disconnected from the actuators during the rigging process. The surfaces are rigged either to a reference point on the fuselage or to another surface (the Production Zero Reference point) and then reconnected to the actuators. An example of the stabilator rigging reference point is presented in figure 1.

A flight control surface is considered to be mis-rigged if the distance between the Production Zero Reference point and the reference on the surface is beyond the allowable rigging tolerance. Rigging is performed on all flight control surfaces except the LEF's by converting the amount of the mis-rig in inches to a prescribed number of turns on the actuator rod end.

Recent Discoveries

NAWC-AD used the F/A-18 simulation to collect uncommanded roll rate data for varying amounts of mis-rig on each flight control surface. This was accomplished by adding a bias to the surface to be mis-rigged to the FCC's calculated surface position commands. This biased surface position was then used for all further calculations, including aerodynamic calculations, feedbacks, etc. The bias was added to every frame to simulate a constant mis-rig. The simulator data show that small changes in the rigged position of a flight control surface result in a unique relationship between uncommanded roll rate and airspeed. Therefore, if the uncommanded roll-off behavior of an airplane is obtained, the information could be used to identify the actual flight control surface causing the uncommanded rolling moment. The simulator data for the CR configuration is presented in figure 2.

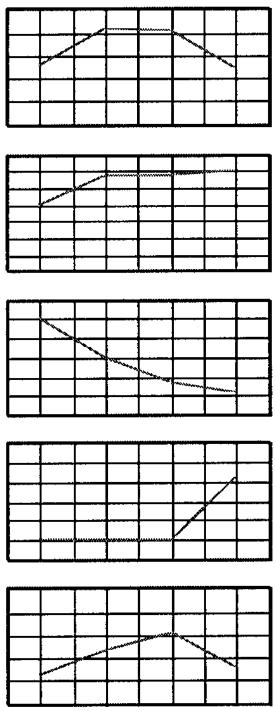


Figure 2
SIMULATOR MIS-RIG DATA

Flight Test Techniques

The flight test method used to gather data on uncommanded roll-off behavior is extremely simple. First, the pilot sets all lateral and directional trim to zero prior to take-off and refrains from trimming in flight. Once airborne, the pilot stabilizes at 200 KCAS, releases the stick, then records the time for 30 deg of bank angle change. This procedure is then repeated at 300, 400, 500, and 550 KCAS. Post-flight, the time to roll 30 deg is converted to an average roll rate and plotted vs. airspeed. The roll rate trace is then compared to the simulator data to identify the suspect surface. Since the roll rate traces are unique for each flight control surface, identification of the suspect surface is simple.

Case Studies

The simulator data has been used successfully by NAWC-AD to identify which flight control surface was causing uncommanded roll rates. Two NAWC-AD and two fleet F/A-18 airplanes were restored to acceptable levels of handling qualities by adjusting the flight control surface rigging within the published tolerances, based on a comparison of the flight data to simulator data.

Case Study #1

One NAWC-AD F/A-18A exhibited a strong tendency to roll to the right after take-off and required constant re-trimming in flight. A standard F/A-18 take-off is in configuration PA1/2. On this airplane, the roll rate in PA1/2 quickly rose to 3 deg/sec by 220 KCAS. Consequently, most pilots started trimming out the uncommanded roll immediately after take-off. When the configuration change to CR was made at approximately 200 KCAS, the uncommanded roll rate should have been zero; however, the trim input while in PA1/2 carried over into CR and trim in the opposite direction was required. Once trimmed for slow speed CR flight conditions, a high speed dash (above 450 KCAS) would result in an unacceptable amount of uncommanded right roll (15 deg/sec by 550 KCAS) that would require re-trimming. Pilots associated the constant requirement for trimming as behavior indicative of a "bent" airplane. When the NAWC-AD test team compared the in-flight data to the simulator data (figure 3), the LEF's were identified as the probable cause of the uncommanded roll rate.

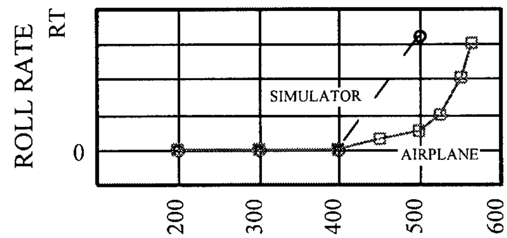


Figure 3
CASE STUDY #1
COMPARISON OF FLIGHT DATA TO SIMULATOR DATA

An initial check of the LEF rigging confirmed that the LEF's were correctly rigged to the center of the reference rivet. The rigging of the LEF's was adjusted to counter the uncommanded roll rate. The left LEF was raised 0.04 inches to the top of the reference rivet and the right LEF was lowered 0.04 inches to the bottom of the reference rivet. These changes are within the published tolerance band for rigging the LEF's. The flight test results for the CR configuration before and after the re-rig are presented in figure 4. The uncommanded roll rate was reduced to less than 5 deg/sec at speeds up to 550 KCAS. NAWC-AD pilots now find the handling qualities of this F/A-18A acceptable for all flight profiles.

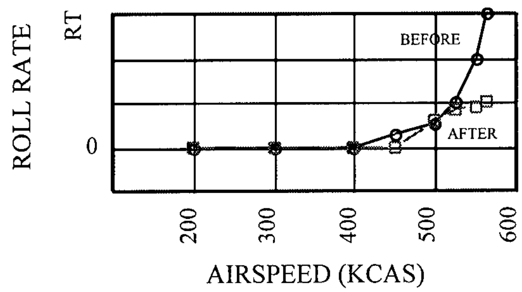


Figure 4
CASE STUDY #1
CR FLIGHT DATA

Case Study #2

A fleet squadron was also experiencing uncommanded rolling moments on two of their F/A-18A airplanes. Squadron pilots reported that straight "over the top" maneuvers were impossible to perform and any attempt to roll left at high AOA would result in a departure from controlled flight. The squadron had become aware of the recent advances made at NAWC-AD in correcting uncommanded roll-off problems and requested assistance to restore their F/A-18A airplanes to acceptable levels of handling qualities for ACM training missions.

One airplane was rigged twice and evaluated three times. The first rigging was required after it was confirmed that eight of ten flight control surfaces were rigged beyond published tolerances. The NAWC-AD test team also noted a significant amount of freeplay in all four LEF transmissions.

The airplane was flown prior to the first rigging to assess the handling qualities of the airplane and to quantify the complaints of the squadron pilots. The airplane exhibited a strong tendency to roll and yaw to the right above 25 deg AOA. By 35 deg AOA, the right roll and yaw rates were uncontrollable, as characterized by the NAWC-AD test pilot. Figure 5 presents the roll rate data and figure 6 presents the maneuvering flight data. The maneuvering flight data (figure 6) confirmed the squadron's most significant complaint, which was the inability to perform straight loops or any left rolling scissors maneuvers above 25 deg AOA and below 150 KCAS.

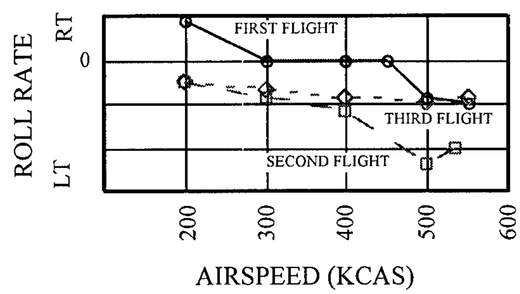


Figure 5
CASE STUDY #2
CR FLIGHT DATA

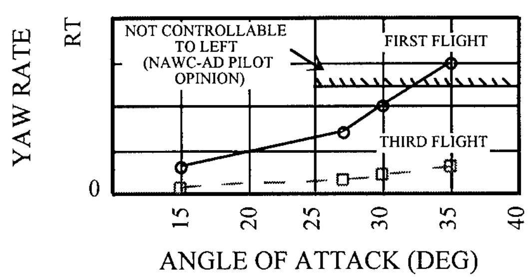


Figure 6
CASE STUDY #2
MANEUVERING FLIGHT DATA

A second flight was flown on the airplane after a complete re-rig of the flight control surfaces. The results from this flight are presented in figure 5. While the CR roll rate trace shows a significant amount of roll rate, the overall aircraft handling qualities were an improvement over those reported by the squadron's pilots. There was no maneuvering flight data collected on this flight; however, the NAWC-AD test pilot reported that although the yaw rate problem at high AOA was not ideal, it was tolerable. A comparison of the simulator data to the data from the second flight revealed that the probable cause was a TEF mis-rig in the mid-speed range and a LEF mis-rig in the high speed range. The NAWC-AD test pilot also noted that in flight the outboard LEF's were noticeably out of alignment with respect to the inboard LEF's, due to the effects of air loads on the LEF freeplay. The TEF's and the outboard LEF's were adjusted to correct the adverse handling qualities.

The data from the final flight are presented in figures 5 and 6. The roll rate in configurations PA and PA1/2 was reduced to insignificant levels (< 2 deg/sec) and the highest roll rate observed in configuration CR was 5 deg/sec. This was considered acceptable by the NAWC-AD team. The yaw rate at high AOA during maneuvering flight was greatly reduced. The NAWC-AD test pilot was able to perform slow speed "over the top" maneuvers with no difficulty. Left rolling scissors, once impossible, were now easily flown at speeds below 150 KCAS and above 25 deg AOA.

Conclusions

NAWC-AD believes that in many cases the cause of uncommanded rolling moments in F/A-18 airplanes can be identified and corrected using the techniques described above. To date, four aircraft that had exhibited uncommanded roll rates and unacceptable handling qualities have been restored to acceptable levels of handling qualities simply by adjusting the flight control surfaces within the published tolerances. A flight test program is underway to formalize the procedures to identify and correct the cause of uncommanded rolling moments for fleet use. The goal is to provide the fleet with a simple method to collect uncommanded roll rate data during functional check flights in order to identify the flight control surface causing the uncommanded rolling moment, and to correlate these uncommanded roll rates with "turns on the actuator rod end" for maintenance action. This procedure will greatly simplify required maintenance actions by replacing the hit-or-miss techniques currently employed with a proven procedure with predictable results.

Multiple Surfaces

While there is no data to support the identification of suspect flight control surfaces when more than one surface is causing the uncommanded roll, NAWC-AD is developing a method that will ease the identification process. The functional check pilot will provide an assessment of the overall characteristic of the roll rate (i.e., did the airplane tend to roll faster at high or low airspeeds). The overall assessment should lead the maintenance crew to the one surface which is causing the most significant roll rates, without ever using the roll rate traces. After the rigging of this surface is adjusted another functional check flight will be flown, and the rigging evaluated once again. The cause of any remaining roll rate can be identified in the same manner. While this method may require more than one flight to correct the roll-off problem, it is formalized with a set of procedures that can be used at the lowest level of maintenance and can be applied to even the most difficult cases: multiple surfaces causing uncommanded roll-off.

Other Considerations

Mis-rigged flight control surfaces are not the only possible cause for uncommanded roll and yaw problems. Roll and yaw at high AOA (above 45 deg) is sometimes characterized by a rapid nose slice and occurs as a result of forebody asymmetries, such as repaired or non-concentric radomes. Uncommanded roll during maneuvering flight can occur if the right and left LEF rate of travel is not equal. NAWC-AD is investigating these alternate causes for uncommanded roll-off in the same flight test program.

Lessons Learned

- Highly augmented fly-by-wire aircraft are susceptible to uncommanded roll-off problems that can easily be isolated by analyzing the wind tunnel data or flight simulation.
- Many fleet squadrons are unaware of the implications of minor rigging adjustments on aircraft handling qualities and incorrectly assume an aircraft with uncommanded roll-off problems is bent and therefore not correctable.
- The large control surfaces used on modern aircraft to enhance slow speed flight can cause large rolling and yawing asymmetries with very small mis-rigged positions (on the order of hundredths of an inch).
- High fidelity simulation of mis-rigged control surfaces can be used to produce unique roll rate vs. airspeed traces that can act as a blueprint to identify suspect control surfaces on the aircraft.
- The flight test methods used to identify rigging problems on complex aircraft are extremely simple to execute.
- Conversion of the roll rate vs. airspeed data to "turns on the actuator rod end" will greatly simplify maintenance procedures by eliminating the variability of rigging techniques and will expedite the rigging process.
- The techniques that have been demonstrated for reducing uncommanded rolling moments in the F/A-18 can be applied to all aircraft.

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